Closed-loop system identification experiments of the C-III emission front response to deuterium fueling in TCV

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Closed-loop system identification experiments of the C-III emission front response to deuterium fueling in TCV

Assessing (non)linearity and compensating for controller influence

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Motivation: heat exhaust challenge

EUROfusion roadmap mission-2: Heat-exhaust systems
• Capable of withstanding the large heat and particle fluxes
• Allow as high performance as possible from the core plasma.
• Achieved by producing ‘detached’ divertor conditions maintained by an active control system.

Controller design requires
• Understanding of the dynamics of the exhaust-plasma
• Control-oriented modelling of the to be controlled system

This contribution
• We use closed-loop system identification to identify the local dynamic response of the TCV exhaust plasma to deuterium (D$_2$) gas injection around different position operating points
• The results test the linearity of the dynamic response of the exhaust plasma.

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**Introduction: System Identification**

- **System Identification** is a range of statistical methods to obtain mathematical models of dynamics systems from measured data. These can be used for off-line controller design.
- One way is the use of periodic perturbations applied to the input of a system $u$, and measure the output of that system $x$, giving data points of its *local* response $\hat{H}(f[\text{Hz}])$.
- For non-linear system the response depends on the operating point.

**Example:**

5 Hz sinusoid $u$ applied to $x$:

\[ \frac{\delta x}{\delta t} = -x^3 + u \]

Local linearization:

\[ \frac{\delta \hat{x}}{\delta t} = -3\bar{x}^2 \cdot \hat{x} + u \]

The response of the system to a 5 Hz sinusoid is shown, with the response increasing with the operating point $\bar{x}$.
Method: identification in closed-loop

- The C-III emission front location along the divertor leg is used as a measure of detachment progression, and can be controlled in real-time using the multi-spectral imaging diagnostic MANTIS [1,2].

- We use closed-loop system identification to identify the local dynamic response of the C-III front to deuterium (D$_2$) gas injection in the divertor at different position operating points.

- A controller is used to reach these operating points, we remove the controller influence on the results using the three-point method [4]:

  $$ u \quad d = \frac{1}{1 + HC} = S(f') $$
  $$ e \quad d = -\frac{H}{1 + HC} = -PS(f) $$

\[ PS(f) \quad S(f) = H(f) \]

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We need to take into account all facets of the control loop which introduce dynamics.
- Piezo-electric valve (V)
- Real-time image processing (RT)
- Collapsed into an equivalent controller $\hat{C}$ and plant $\hat{H}$.

Control CIII front position to desired location from 0.8s
Perturbation introduced at 0.9s on the disturbance channel using multi-sine excitations.
Results

- Results shown in a Bodeplot: relative phase and amplitude of output to input over frequency.
- No strong changes in dynamics are observed over operating height of the CIII front.

Perturbation height

<table>
<thead>
<tr>
<th>Height</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09m</td>
<td>0.17m</td>
<td>0.23m</td>
</tr>
<tr>
<td>0.17m</td>
<td>0.22m</td>
<td>0.20m</td>
</tr>
</tbody>
</table>

openloop result [5]

Performed closed-loop system identification of the CIII front response to D$_2$ fueling in the TCV tokamak around different operating heights.

- In both L-mode and H-mode no significant change of dynamics is observed when changing operating height, indicating the response is (dominantly) linear over a large operating range for timescales up to 40 Hz.

- Implies a single (linear) controller is sufficient in a single scenario.

- Are these results extrapolatable to emission front control with impurities?

Conclusion